ABSTRACT

APPLYING FUNDAMENTAL CONCEPTS TO THE ENGINEERING DESIGN OF APPLIANCE BURNERS

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Fundamental concepts relating burner design factors and gas composition to the conventional flame characteristics of lifting, yellow tipping, and flashback are discussed.

Design relationships are developed from the basic critical boundary velocity gradient theory with respect to lifting flames. Such burner design factors as port size, depth, and spacing; port loading and primary aeration; and gas composition are taken into account.

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There are many areas in the gas industry where there is a definite need to bridge the gap between fundamental concepts and engineering application. As an example, the design of atmospheric gas burners for domestic appliances requires a judicious balance of opposing characteristics. A design directed toward eliminating any propensity for lifting flames might introduce a tendency for yellow tipping flames, or a design for high primary air injection could be liable to flashback. A knowledge of the quantitative effects of all pertinent variables is, therefore, necessary to achieve a desired balance in design. The following is an attempt to interpret fundamental concepts in such a manner that they might be easily applied in the engineering design of burner port areas.

The nature of the port area for any given application is dictated by limiting conditions which produce critical flame characteristics such as lifting, yellow tipping, and flashback. A typical flame characteristic diagram is shown in Figure 1, which describes limiting conditions in terms of primary aeration, expressed as a per cent of the air required in a stoichiometric mixture and port loading in Btu per hour per square inch of port area. Any change in variables such as port size, depth, or spacing will displace these limit curves so as to either increase or decrease the area of the stable, blue flame zone. Ideally, of course, this zone should be as large as possible.

The flame characteristic diagram for a given burner operating on a given gas is fixed. If at any time the operating point of the burner, as defined by port loading and primary aeration, lies above the lifting limit curve, lifting flames will occur. When the operating point lies below the yellow tip limit, the flames will exhibit yellow tips, and flashback will take place if the operating point lies to the left of the flashback limit curve.

The general effects of burner design variables and gas composition on these limiting flame characteristics have been known for many years. Lifting tendencies are reduced by the use of larger, deeper, more closely spaced ports. Yellow tipping of flames, on the other hand, is reduced by using smaller, more widely spaced ports. The use of several rows of ports generally raises the yellow tip limit, but does not affect lifting tendencies, provided even distribution of air-gas mixture to all the ports is provided. Port depth does not appear to have an effect on yellow tipping tendencies. Flashback tendencies appear to be reduced by the use of smaller, deeper ports. The use of closer port spacings apparently results in a hotter operating burner head temperature, which in turn promotes flashback. At the same air-gas mixture temperature, however, port spacing does not appear to affect flashback.

Burning velocities of fuel gases affect lifting and flashback tendencies. Slower burning gases are more critical in regard to lifting flames, while flashback occurs more readily with faster burning gases. Each fuel gas has its own yellow tipping characteristics.

Lifting and flashback are flame stability phenomena. As such, they are dependent on the relative velocities of air-gas mixture flowing out of the port, and the counter propagation of flame into the air-gas mixture in the ports and burner head. With normal flames, equilibrium between these opposing factors generally takes place a short distance above the burner port. This distance between the burner port and the base of the flame is generally referred to as the "dead space".

Yellow tipping, on the other hand, is a completely different phenomenon. Each fuel gas requires a certain amount of air to completely eliminate yellow tips from appearing in its flames. This air can be obtained either as primary air or as secondary air diffusing to the point where yellow tips appear in the flames. Port size, spacing, and the number of rows of ports affect the degree to which secondary air can be utilized to eliminate yellow tipping. This, in turn, determines the primary air necessary to make up a deficiency of secondary air, and hence establishes the so-called yellow tip limit of the burner.

Extensive studies of flame characteristics and burner design have been made at the A.G.A. Laboratories, the U. S. Bureau of Mines, and other institutions. In February, 1958, A.G.A. Laboratories Research Bulletin 77, "Influence of Port Design and Gas Composition on Flame Characteristics of Atmospheric Burners", was published. This bulletin not only describes recent burner design studies, but correlates the results of those studies with the results of previous investigations. For the purposes of the present discussion, only lifting characteristics of flames will be considered.

The critical boundary velocity gradient theory was used as a basis of studies of lifting flames. This theory states that blowoff (lifting) will occur when the flow velocity gradient at the wall of a port exceeds the burning velocity at all points around the port.

The expression for the boundary velocity gradient, g, is derived by equating the pressure drop per unit length of channel to the retarding viscous force at the wall per unit length of channel:

$$\mu g \, 2 \pi R = \left(\frac{\Delta P}{\ell} \pi R^2\right) = \rho f \, V^2/4 \pi R^3 \qquad (1)$$

where:

μ = viscosity, pound second per square foot,
g = boundary velocity gradient, 1/sec,
R = port radius, feet,
$(\Delta P/\ell)$ = pressure drop per unit length of port, pounds per square foot per foot,
ρ = mass density, slugs per cubic foot,
f = friction factor, dimensionless, and
V = volumetric flow rate, cubic feet per second.

Introducing Reynolds' number as $Re = 2 V \rho / \mu \pi R$, equation (1) becomes:

$$g = \frac{f \, V \, Re}{16 \pi R^3} \qquad (2)$$

Equation (2) is, therefore, a generalized equation for the boundary velocity gradient. Substituting the Hagen-Poiseuille relationship for parabolic (laminar) flow, $f = 64/Re$, in equation (2) obtains:

$$g = \frac{4\ V}{\pi\ R^3} \tag{3}$$

This is the expression for the boundary velocity gradient for deep circular ports. If the value of the volumetric flow at a condition of lifting flames, V_L, is substituted in equation (3), the equation then defines the critical boundary velocity gradient for lifting, g_L, for deep circular ports.

It should be emphasized that this critical boundary velocity gradient for lifting is a fundamental characteristic of the given gas, and as such is independent of burner design. In other words, for any given primary aeration, there is a definite critical boundary velocity gradient at which lifting will occur, regardless of the design of the port. Advantage can be taken of this fact to obtain expressions relating port geometry to lifting flames for shallow and non-circular port forms.

Equation (3) may be expressed in terms more generally used in the gas industry as:

$$g = \frac{1.92\ I\ a\ (1 + A/G)}{\pi\ R^3\ H} \tag{4}$$

where:

g = boundary velocity gradient, 1/sec,
I = port loading, Btu per hour per square inch of port area,
a = port area, square inches,
A/G = air-gas ratio,
R = port radius, feet, and
H = heating value of fuel gas, Btu per cubic foot.

For an individual port, $a = \pi R^2$ and equation (4) reduces to:

$$g = 1.92\ \frac{I}{R}\ \left(\frac{1 + A/G}{H}\right) \tag{5}$$

At the limiting conditions for lifting flames for a given fuel gas and a given primary aeration, the fraction $(1 + A/G)/H$ is a constant, K, so that equation (5) can be further reduced to:

$$K\ g_L = \frac{3.84\ I_L}{D} \quad \text{for deep circular ports} \tag{6}$$

where:

K = a function of the primary aeration and heating value, $H/(1 + A/G)$,
g_L = critical boundary velocity gradient for lifting, 1/sec,
I_L = port loading at the lifting limit, Btu per hour per square inch of port area, and
D = port diameter, inches.

The critical boundary velocity gradient for a given gas with a given primary aeration is a constant. Equation (6) then states that the limiting port loading at the lifting limit is directly proportional to the port diameter.

The equation also indicates that lifting limit curves (plotting per cent primary aeration versus port loading) would be parallel curves. Figure 2 demonstrates that this is true for port sizes which might be used in contemporary drilled port burners.

It will be noted that the lifting limit curve in Figure 2 for the 1/4 inch diameter port is not parallel to the other curves, but falls off more abruptly at higher port loadings. Uneven distribution of air-gas mixture flow velocities in larger ports lowers the lifting limit of that port. Lifting will occur at any point around the port rim where the critical boundary velocity gradient for lifting is reached, even though flames may be stable at all other points around the port. In calculating port loading, even distribution must be assumed and the port loading obtained simply by dividing the heat input by the port area. Uneven distribution resulted in "incipient lifting", i.e., lifting at one point on the port with the flame hanging on to the remainder of the port rim. This condition was also noted with large rectangular ports. Within the port sizes generally used in contemporary drilled port burners (No. 50 to No. 20 DMS), however, parallel lifting limit curves for different port diameters were observed.

It is possible, therefore, to represent the lifting limits of various individual ports of various sizes by a single limit curve by plotting $\phi\ I_L$ versus primary aeration at lifting, where I_L is the limiting port loading and ϕ is a multiplying factor dependent on the port geometry. For deep circular ports, ϕ would equal 1/D, where D is port diameter.

It was also observed that parallel lifting limit curves were obtained for various port depths, up to a limiting depth. The lifting limit of ports deeper than this limiting depth were found to be the same. Figure 3 illustrates a typical example of this trend. Similarly, parallel lifting limit curves were observed for rectangular ports of various widths, lengths, and depths, when two of these geometric factors were held constant and the third varied. It appeared, then, that geometric multiplying factors could be obtained for these various port designs so that a single lifting limit curve could be used for all such port designs.

As a first step in these determinations, the critical boundary velocity gradient for Cleveland natural gas was calculated (by use of equation (3)) from observed lifting limits with very deep ports. All of these lifting studies were made with a relatively cold burner, since this is the most critical condition for lifting flames. Figure 4 shows these critical boundary velocity gradients for Cleveland natural gas.

Equation (2), when applied to a condition of lifting flames, can be modified to include a term for port loading to become:

$$g_L = \frac{f\ Re\ I_L\ a}{16\pi R^3} \times \frac{1 + A/G}{H} \times \frac{1728}{3600} \qquad (7)$$

At any given primary aeration for Cleveland natural gas, equation (7) would reduce to:

$$K\,g_L = \frac{0.06\ f\ Re\ I_L}{D} \tag{8}$$

where:

D = port diameter, inches, and
K = a function of the given primary aeration.

The values of f at lifting conditions for various port geometries were then evaluated by observing the lifting limits for a number of ports. For each corresponding value of primary aeration at the lifting condition, values of the critical velocity gradient, g_L, were picked from the curve of Figure 4. Values of f could then be solved for in equation (8), since all of the other factors in the equation are known from measurement.

Figure 5 shows the observed empirical relationship between the expression f Re and port geometry for various circular ports. The horizontal segment of the curve represents data obtained with relatively deep ports in which laminar flow takes place. The sloped portion of the curve, which can be represented by the expression $f = 305\ D/Re\ \sqrt[4]{d}$, applies to relatively shallow ports. Substitution of the latter relationship in equation (8) obtains:

$$K\,g_L = \frac{18.3\ I_L}{\sqrt[4]{d}} \quad \text{for shallow circular ports} \tag{9}$$

As was previously pointed out, the critical boundary velocity gradient for a given gas and primary aeration is a function of the burning characteristics of the gas, and as such is independent of the port geometry. Thus, equations (6) and (9) can be equated so that:

$$\frac{3.84\ I_L}{D}\ \text{for deep circular ports} = \frac{18.3\ I_L}{\sqrt[4]{d}}\ \text{for shallow circular ports} \tag{10}$$

If the multiplying factor (ϕ) for deep circular ports is taken as $\phi = 1/D$, then this factor for shallow circular ports would be $\phi = 4.77/\sqrt[4]{d}$.

It is realized that the transition from "deep" to "shallow" circular ports takes place in a gradual process, rather than at a sharp breaking point. This transition zone is illustrated in Figure 5 by the curved line joining the straight horizontal and sloped lines. It was found, however, that an arbitrary limiting point could be determined by the intersection of the extensions of the straight horizontal and sloped lines of Figure 5. The "deep" port multiplying factor can be used with good accuracy for ports to the left of this arbitrary point, and the "shallow" port expression can be used for ports to the right of this point.

A similar treatment was made with rectangular ports, and empirical geometrical multiplying factors were determined. Expressions obtained for the factor ϕ, for circular and rectangular ports are summarized in the following:

$$\text{Deep circular ports } (D/\sqrt[4]{d} < 0.21),\ \phi = \frac{1}{D} \tag{11}$$

Shallow circular ports $(D/\sqrt[4]{d} > 0.21)$, $\phi = 4.77/\sqrt[4]{d}$ (12)

Deep rectangular ports $(\frac{De}{d} < 1.0)$, $\phi = \frac{1.44\ (n + 1)}{n\ \sqrt{W}}$ (13)

Shallow rectangular ports $(\frac{De}{d} > 1.0)$, $\phi = \frac{2.88\sqrt{W}}{d}$ (14)

where:

- D = port diameter of circular ports, inches,
- d = port depth, inches
- De = equivalent port diameter of rectangular ports, inches = $2\ n\ W/(n + 1)$,
- W = rectangular port width, inches, and
- n = ratio of rectangular port length to width.

These expressions for ϕ were applied to all the lifting limit data observed for Cleveland natural gas with individual ports to obtain the average generalized lifting limit curve illustrated in Figure 6. For port sizes generally used in contemporary burners, the observed lifting limits generally fell within 3 percentage units of primary aeration of the curve.

The use of multiple drilled ports affects the lifting limit of a burner. In general, closer port spacing raises the lifting limit. Of course, there is a maximum port spacing above which the ports can be considered to act as individual ports. This effect is apparently due to a reduction in the quenching of the flame reaction by the surrounding air above the port.

A simple experiment at the A.G.A. Laboratories illustrated this effect. An electrically heated coil was placed around a port. The coil was so spaced that it would not ignite the air-gas mixture issuing from the port. The lifting limit of the port was raised considerably when the coil was heated electrically.

With a multiple drilled port burner, adjacent flames apparently create the same effect as the heated coil. The end ports of bar burners, which are influenced by adjacent ports on only one side, generally lift first. Some such lifting can be tolerated if combustion or carryover is not impaired when the burner is first lighted. Because of this, the lifting limit of multiple port burners was arbitrarily chosen as the point at which three or four of the end ports lifted.

Figure 7 illustrates that lifting limit curves for multiple port burners were found to be essentially parallel curves. A multiplying factor can then be determined for various port spacings in order to obtain a single lifting limit curve.

The values of these factors, in relation to the individual port curve of Figure 6, were determined to be: 0.88 for 1/4 inch or greater; 1.0 for 3/16 inch; 1.12 for 1/8 inch; and 1.82 for 1/16 inch spacing of ports edge-to-edge.

The use of multiple rows does not appear to affect lifting characteristics, provided the port spacing multiplying factor for the smallest spacing between ports (whether in the rows or between rows) is used in entering Figure 6.

It has been observed that within the span of port loadings generally used in contemporary drilled port burners (10,000 to 60,000 Btu per hour per square inch of port area), lifting limit curves for various gases were essentially parallel curves. This trend was noted in burner port design studies conducted at the U. S. Bureau of Mines, and in investigations conducted at the A.G.A. Laboratories. Figure 8 illustrates the lifting limits obtained for various gases at the U. S. Bureau of Mines.

Thus, the lifting characteristics of a fuel gas may be expressed in terms of an equivalent rate factor relative to the lifting characteristics of a reference gas. The effects of gas composition on lifting characteristics were calculated for a limited number of gases. The principle involved, however, can be applied to other gases which might be used in the field. Information which can be used to determine the equivalent rate factor for a number of gases can be found in several publications. Two such publications are the U. S. Bureau of Mines' Report of Investigation 5225, "Fundamental Flashback, Blowoff, and Yellow Tip Limits of Fuel Gas-Air Mixtures", and A.G.A. Laboratories Research Bulletin 36, "Interchangeability of Other Fuel Gases with Natural Gas". The method of using the information contained in these reports is described more fully in A.G.A. Laboratories Research Bulletin 77.

Tables have been prepared which relate the lifting characteristics of designs generally used in contemporary burners to those of an arbitrarily chosen reference burner.

Several factors affecting the lifting characteristics of burners are still relatively unexplored. Uneven distribution of air-gas mixture to the ports will always result in a lower lifting limit than values calculated from the equations previously discussed. Port loading must be considered as simply the total heat input to the burner divided by the total port area in design calculations. Overrated ports will, therefore, lift at a lower primary aeration than the calculated value.

The design methods described in A.G.A. Laboratories Research Bulletin 77 are for open room conditions. Combustion chamber environment has some effect on lifting characteristics. A current water heater research investigation at the A.G.A. Laboratories is considering this aspect of the problem.

Burner design research is a continuing process. By applying fundamental concepts, the engineering design of appliance burners is, with time, becoming less of an art and more of a science.

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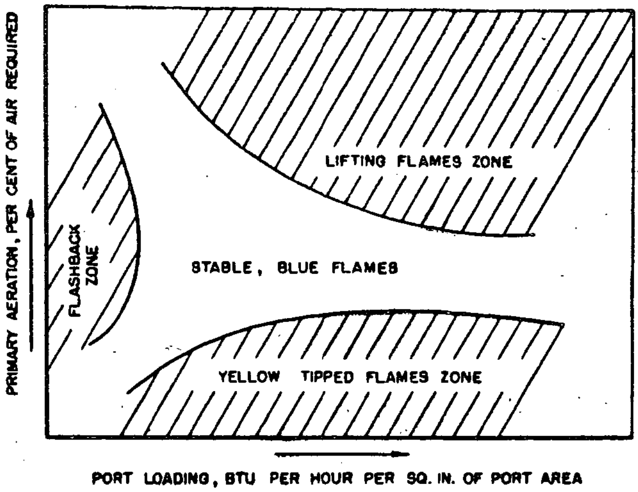

Figure 1 Typical Flame Characteristics Diagram, Showing Lifting, Yellow Tipping, and Flashback Limit Curves.

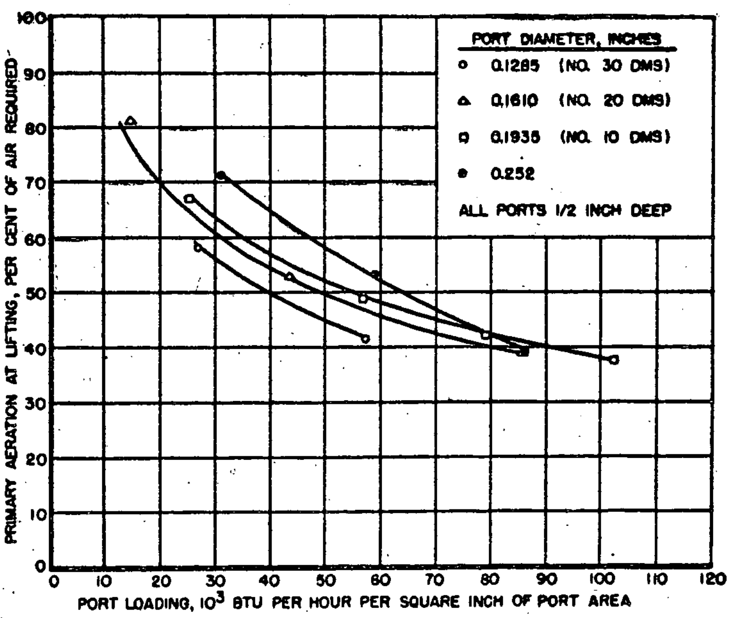

Figure 2 Lifting Limits of Various Individual Circular Ports with Cleveland Natural Gas.

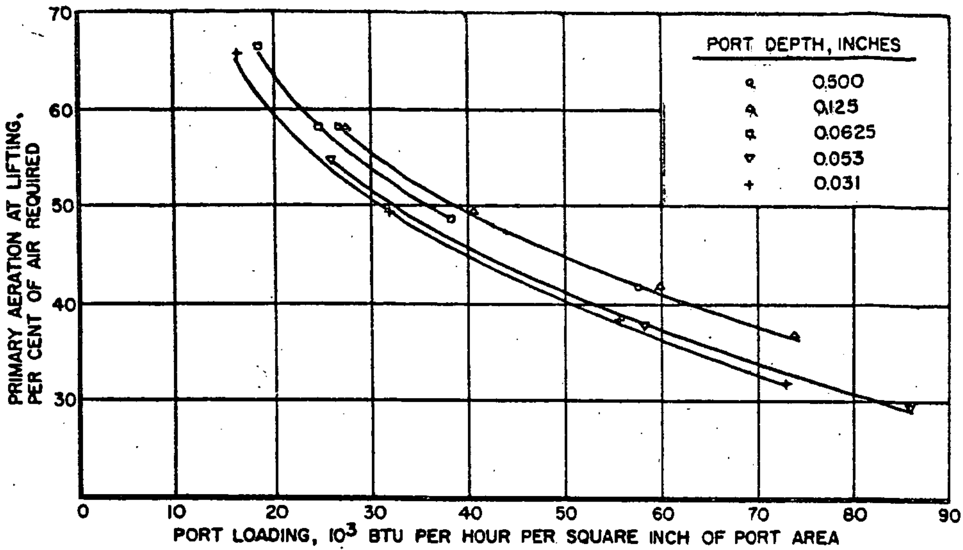

Figure 3 Lifting Limits of a No. 30 DMS Drilled Port with Various Port Depths with Cleveland Natural Gas.

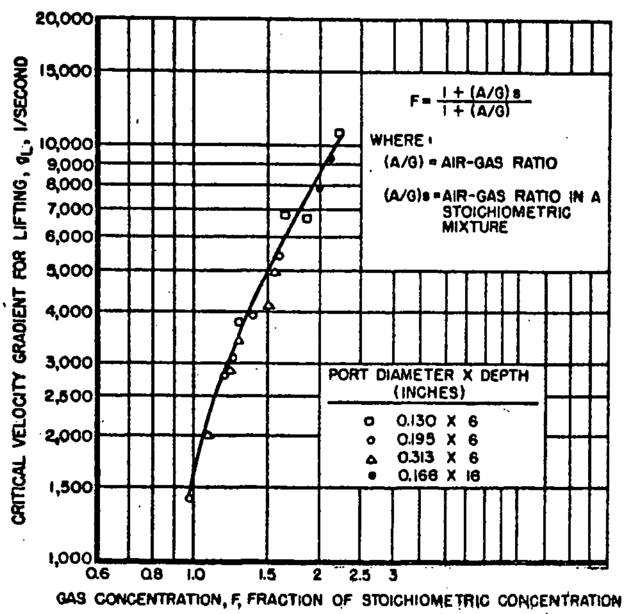

Figure 4 Critical Lifting Boundary Velocity Gradient for Cleveland Natural Gas.

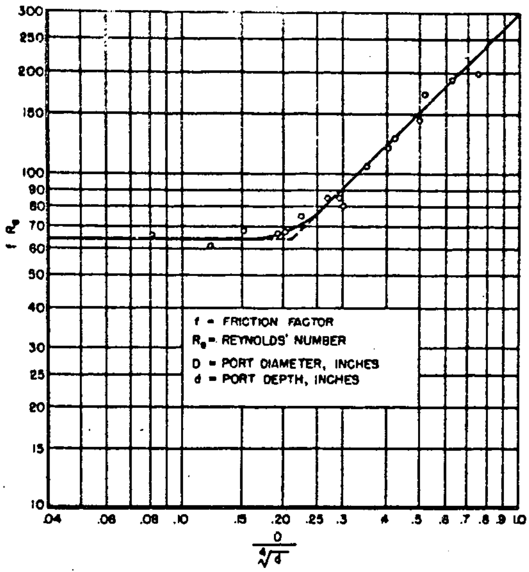

Figure 5 Friction Factors for Various Deep and Shallow Circular Ports with Cleveland Natural Gas at the Lifting Limit.

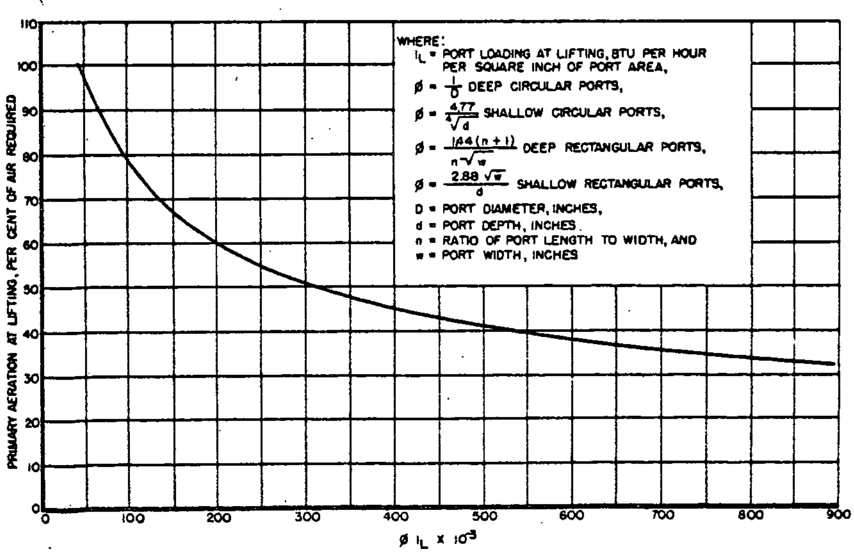

Figure 6 Lifting Limits of Slotted and Circular Ports with Cleveland Natural Gas.

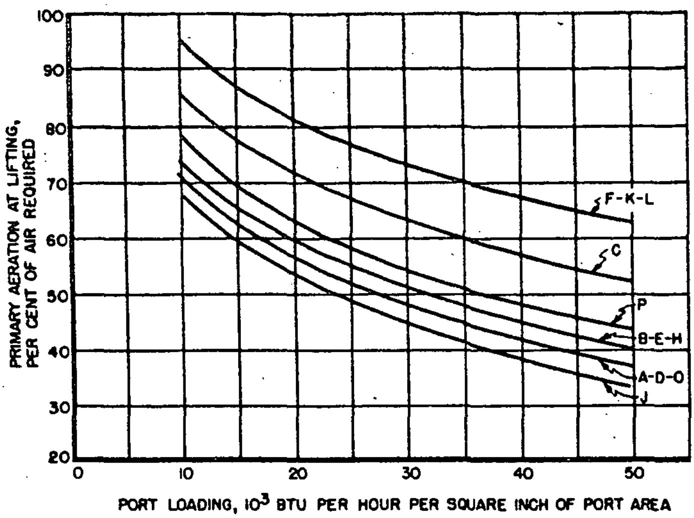

Figure 7 Lifting Limit Curves with Cleveland Natural Gas for Experimental, Multiple Port Burners.

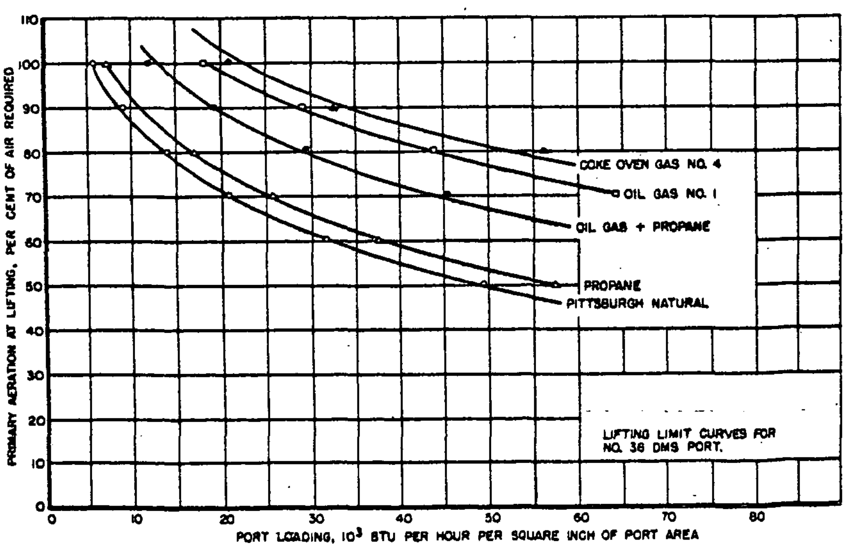

Figure 8 Lifting Limits Obtained at the U. S. Bureau of Mines for Various Fuel Gases.